Tests of Fundamental Symmetries with Neutrons

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Abstract. Because of recent technological developments, new opportunities to test fundamental symmetries using cold and ultra-cold neutrons will become available in the next several years. These tests include studies of the parity-violating hadronic weak interaction, searches for new symmetries beyond the standard model using neutron decay and searches for new sources of Charge-conjugation/Parity (CP) violation through the measurement of the neutron Electric Dipole Moment (EDM).

INTRODUCTION

 Both the observation and violation of fundamental symmetries have played a critical role in the development of the Standard Model of the fundamental interactions. Experiments with free neutrons allow sensitive measurements and tests of a number of symmetries, including parity, Charge conjugation/Parity (CP) and searches for new symmetries beyond the Standard Model. Recent developments in the production of cold and ultra-cold neutrons have provided new opportunities for highly sensitive experiments. I will briefly discuss some new developments in neutron production and summarize the status and plans of existing and future facilities. This will be followed by a summary of the main science objectives within this field and a discussion of the developing program within the US.

NEUTRON TECHNOLOGY

 Very briefly, cold neutrons with wavelengths of approximately 0.4 nm (with velocities about 100 m/s) are produced from the moderation of fast neutrons generated by either nuclear reactors or proton spallation from a heavy target. These neutrons can then be transported as beams to experiments using neutron guides. The advantages of cold neutrons are their high flux and high polarization using new techniques (polarized ^{3}He and advanced supermirrors) that are under development. Ultra-Cold Neutrons

(UCN) are neutrons with wavelengths longer than 50 nm (with velocities less than about 8 m/s). Neutrons of this velocity can be trapped within certain materials and be highly polarized with modest magnetic fields of 6 T. Materials have been developed that allow trapping of UCN for times on the order of hundreds of seconds. A new source of UCN based on proton spallation and moderation using solid deuterium has been demonstrated recently (Ref. 1). This technique along with a similar technique based on superfluid He may allow significant increases (factors of 100-1000) in the attainable densities of UCN.

FACILITIES FOR FUNDAMENTAL NEUTRON PHYSICS

Facilities for testing fundamental symmetries with neutrons are typically based at a large neutron scattering facility whose primary mission is based on condensed matter physics and materials science. Such facilities have been constructed at both research reactors and spallation neutron sources. A summary of existing and planned facilities is listed in Table 1.

TABLE 1. Facilities for Fundamental Symmetry Tests with Neutrons

Facility	Location	Neutron Technology	Facility Status
NG6	NIST (US) Reactor	Cold Beam	Operating
PF1 & PF2	ILL (France) Reactor	Cold Beam and UCN	Operating
FP12 & Area B	LANSCE (US) Spallation source	Cold Beam and UCN	Starting Operations
FNPB	SNS (US) Spallation Source	Cold Beam and UCN	Under Construction
SINQ	PSI (Switzerland) Spallation Source	Cold Beam and UCN	Starting Operations
FRM-II	TUM (Germany) Reactor	UCN	Under Construction
PULSTAR	NCSU (US) Reactor	UCN	Under Construction
LENS	IUCF (US) Nuclear reaction	UCN development	Under Construction
Osaka?, JPARC?	(Japan) Spallation Source	UCN	Under Discussion

THE HADRONIC WEAK INTERACTION

While the leptonic weak interactions are well-characterized by the standard electroweak model, purely hadronic weak interactions require a melding of Quantum

Chromo-Dynamics (QCD) and the electroweak theory. At low energies these processes are non-perturbative and up to now have only been studied in effective theories. These processes are distinguishable from the strong hadronic interactions through the parity violation inherent in the electroweak theory. An early theoretical attempt at estimating the strength of the hadronic weak interactions was undertaken by Desplanques, Donoghue and Holstein (Ref. 2). In this the work the processes could be characterized by six coupling constants: f_π, h_ρ^0, h_ρ^1, h_ρ^2, h_ω^0, h_ω^1 .These couplings were estimated in a quark model and can be best compared with experiment in precision measurements of parity violation in few-body systems. Few-body systems allow comparison with the calculations relatively free of complications from nuclear structure corrections. At present a discrepancy exists in the measurements of the f_π coupling constant. Nuclear decay measurements in ^{18}F and atomic parity violation in [133]Cs give vastly different results (differing by about an order-of-magnitude). A new measurement of f_π in polarized neutron capture on protons (n + p→d + γ) promises to resolve this discrepancy. This experiment is being commissioned at Flight Path 12 (FP12) at the LANSCE facility and is planning to take its high statistics data at the Fundamental Neutron Physics Beamline (FNPB) at the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory. A new measurement of neutron spin rotation in [4]He at the National Institute for Standards and Technology (NIST) will also provide sensitivity to f_π and several other parameters.

NEUTRON BETA-DECAY

Neutron beta decay can be described within the Standard Electoweak Model. Precision measurements of the decay properties allow sensitive tests of this model and deviations from the expected decay can be signatures for new physics beyond the Standard Model. An example of constraints on Supersymmetry models from beta decay data is discussed in Ref. 3. In this work the measurements of the Cabibbo-Kobayashi-Maskawa matrix element V_{ud} are used to constrain the parameters of the model. Presently the best measurements of V_{ud} are obtained from the decays of radioactive nuclei. Future measurements of neutron decay may eventually provide the best results for V_{ud} because of the potentially smaller uncertainties for the neutron due to nuclear corrections in the case of radioactive nuclei. The decay distribution can be expressed in terms of a total decay rate Γ_n and a number of correlation coefficients b, a, A, B, D via:

$$d\Gamma = \Gamma_n \left(1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_v}{E_e E_v} + A\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + B\frac{\vec{\sigma}_n \cdot \vec{p}_v}{E_v} + D\frac{\vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_v)}{E_e E_v} \right) \quad (1)$$

Coefficients b and D are zero in the Standard Model, while the other coefficients depend, in different ways, on other parameters. The dependence of neutron decay on V_{ud} can be seen in the expression for the total decay rate:

$$\frac{1}{\tilde{A}_n} = \left(\frac{2\,\partial^3\,\hbar^7}{m_e^5 c^4}\right)\left(\frac{1}{G_F^2 |V_{ud}|^2}\right)\left[\frac{1}{1+3(G_A/G_V)^2}\right]\frac{1}{f(1+\ddot{A}_R)} \qquad (2)$$

where G_F is the Fermi constant which is known from muon decay, V_{ud} is the up-down quark weak coupling from the Cabibbo-Kobayashi-Maskawa (CKM) matrix. G_A/G_V is the ratio of the axial vector to vector weak coupling constant, f is the phase space integral for the decay products and Δ_R is an electroweak radiative correction.

Extraction of V_{ud} using the neutron requires measurement of the neutron lifetime ($\tau_n = 1/\Gamma_n$) and a separate measurement of G_A/G_V. The measurement of G_A/G_V can be accomplished by a measurement of the A correlation from eq. (1). Within the Standard Model, and to leading order, the A correlation is related to G_A/G_V via:

$$A = \frac{-2\ddot{e}(1+\ddot{e})}{1+3\ddot{e}^2} \qquad , \quad \ddot{e} = \frac{G_A}{G_V} \qquad (3)$$

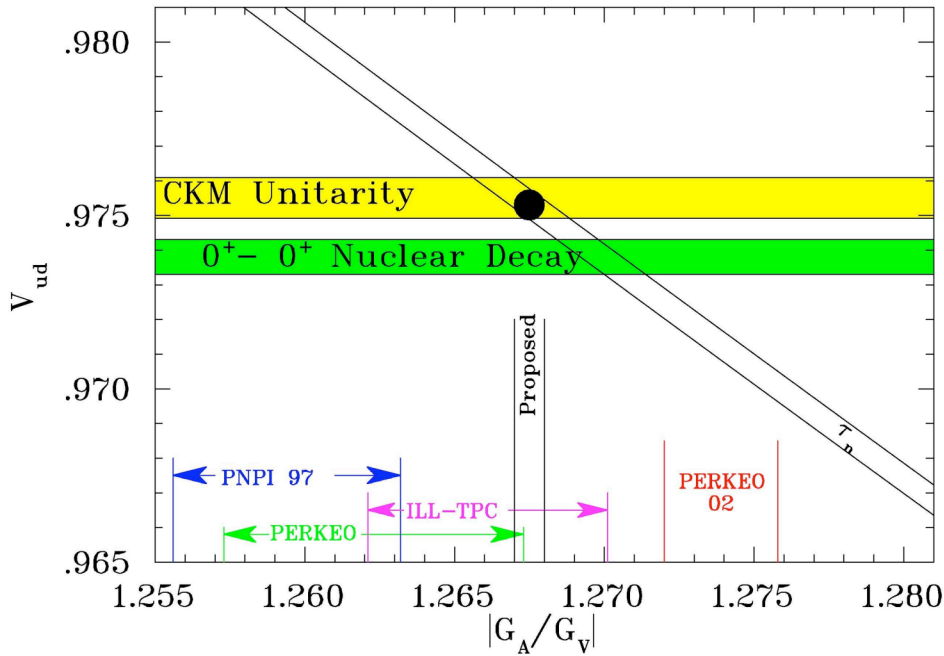The present status of measurements of V_{ud} from neutron decay is shown in Fig. 1.

FIGURE 1. Status of V_{ud} in terms of the neutron lifetime and neutron decay asymmetry measurements based on data from Ref. 4. The solid circle is the proposed measurement at the LANSCE facility in Area B.

While improved measurements of G_A/G_V from the A correlation coefficient are planned at the UCNA experiment at the LANSCE facility and at the FNPB, a recent measurement of the neutron lifetime has suggested that the value of this important quantity is still unresolved. A summary of recent measurements of the neutron lifetime is shown in Fig. 2, where the most recent measurement deviates from the previous average by about six standard deviations. Clearly new measurements of this quantity are necessary in order to resolve this serious discrepancy.
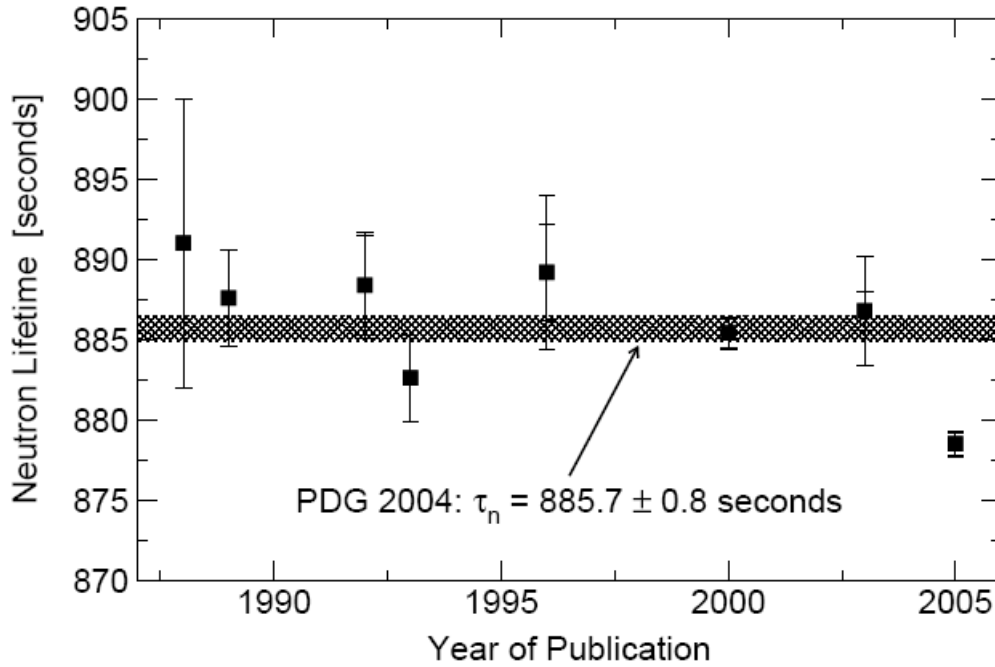

FIGURE 2. Recent measurements of the neutron lifetime. Both cold neutron beams and ultra-cold neutron bottles were used in these experiments. The most recent measurement (Ref. 5) differs from the mean value of the previous measurements by about six standard deviations.

THE NEUTRON ELECTRIC DIPOLE MOMENT (EDM)

The observation of a non-zero neutron Electric Dipole moment (EDM) would provide the first evidence for Time-Reversal violation (and, hence, CP violation via the CPT theorem) in the flavor-conserving sector of the Standard Model. This type of CP violation in baryons may provide an explanation for the matter-antimatter asymmetry observed in the universe.

For more than 50 years, searches for a neutron EDM have yielded no observable signal, even as the sensitivity has increased by eight orders-of-magnitude. The current best upper limit of 6.3×10^{-26} e-cm (at 90% C.L.) (Ref. 6) is about six orders-of-magnitude above the Standard Model prediction. Thus there exists a significant opportunity for observing new physics in searches with improved sensitivity. Some of the proposed extensions to the standard model (e.g., Supersymmetry) predict a value

for the neutron electric dipole moment that is only one or two orders of magnitude below the present limit. A new search then has the potential to severely constrain extensions to the standard model or, if a non-zero value is observed, to provide the first evidence for a neutron electric dipole moment at a level larger than that of the standard model prediction. Such a measurement of a neutron EDM would indicate the existence of a new source of CP violation not currently included in the Standard Model.
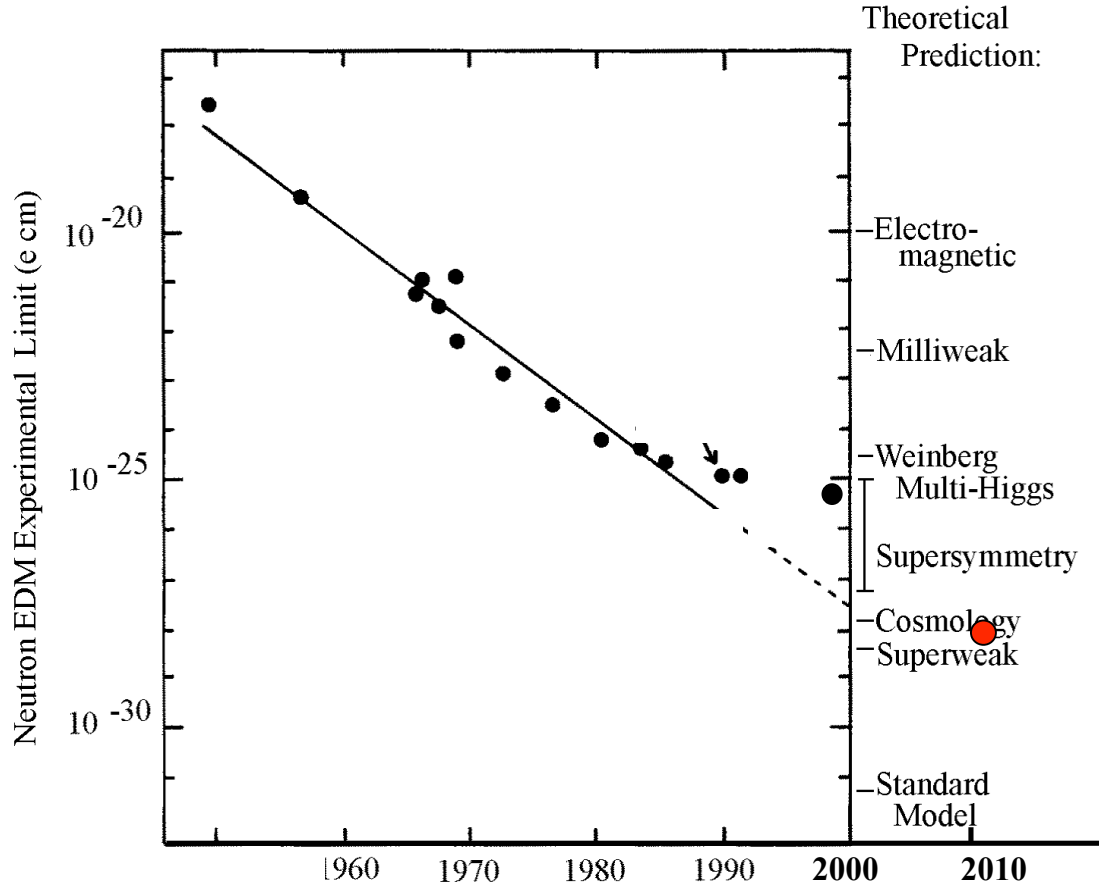

FIGURE 3. Time dependence of the measured upper limit for the neutron EDM. The red circle represents the expected sensitivity from the EDM measurement at the FNPB as described in the text.

Several new measurements of the neutron EDM are being planned including one to be performed at the FNPB at the SNS. This new search will employ ultra-cold neutrons produced via the moderation of cold neutrons in superfluid ^{4}He (with the recoil phonon in the superfluid carrying away the missing momentum and energy). The experiment is based on the magnetic resonance technique of free precession of a magnetic moment in a magnetic field and will also use a novel polarized ^{3}He co-magnetometer. The value of the electric dipole moment can be extracted from the

difference between neutron spin precession frequencies under the influence of parallel and anti-parallel magnetic and electric fields. The proposed sensitivity of the new experiment can be seen in Fig. 3, where the previous upper limits on the EDM are shown vs. the date of the published result. A comparison of the sensitivity of the proposed SNS experiment to the present experiment at ILL is shown in Table. 2. The sensitivity is calculated using:

$$\acute{o}_d \cong \frac{\hbar}{4 \, |\vec{E}| \, T_m \sqrt{mN_{UCN}}} \tag{4}$$

TABLE 2. Comparison of EDM experiments

Experimental Parameter	Present ILL experiment	Proposed SNS experiement
N_{UCN}	1.3×10^4	2×10^7
$\|E\|$ (kV/cm)	4.5 kV/cm	50 kV/cm
T_m (sec)	140	500
M (cycles/day)	270	50
σ_d (e-cm)/day	6×10^{-25}	1.5×10^{-27}

OUTLOOK

New tests of fundamental symmetries using neutrons are underway both in the US and worldwide. Compelling science is anticipated from these studies within the next 5-10 years in measurements of the nucleon-nucleon weak current, neutron beta decay and the neutron EDM.

ACKNOWLEDGMENTS

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